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DEVELOPMENT OF ADVANCED SURFACE ENGINEERING TECHNOLOGIES FOR THE BENEFIT OF MULTIPOINT CUTTING TOOLS

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ABSTRACT

The benefits of applying advanced coatings on both single point and multipoint cutting tools such as improvement of productivity, tool life, machined surface quality etc. have been realised by the surface engineering researchers [1], commercial coaters [2-4] and end users [5]. The demand for advanced coatings in cutting tool industries is continually growing to meet the challenges of high speed machining, dry machining, near net-shape machining, machining of hard-to-cut materials etc.. Advance coatings with excellent properties on flat coupon in a laboratory deposited by modern deposition technologies should not be taken for granted in improving the performance of complex shaped cutting tools [6] in aggressive cutting environments. This is because the end performance of coated cutting tools is not only dependant on the coating itself but also on the substrate material, geometry, surface finish and cutting edge conditions prior to coating deposition. The paper presents case studies with examples of successes and failures of advanced coatings on different multipoint cutting tools (e.g., milling cutters, bandsaws, circular saws, holesaws etc.). The future strategy for developing successful coating technology for cutting tools should be directed towards adopting a systems approach to bridge the communication gap amongst the cutting tool manufactures, tool coaters and end users.

KEYWORDS: Advanced coating; Multipoint cutting tools; Metal Machining

1. INTRODUCTION

At the beginning of 21st century, the cutting tool industry like other manufacturing industries, faces the universal challenge of improving manufacturing economics through the improvement of productivity (i.e., higher material removal rate) and reduction of machining costs (i.e., longer tool life). At the same time, other challenges including machining of hard and difficult-to-cut materials with improved product quality, reduction of environmental pollution from cutting fluids and machining of small parts (micromachining) have further mounted the pressure on cutting tool industries. To combat these challenges several new generation of machining technologies have emerged, as shown in Fig. 1 [7-9].

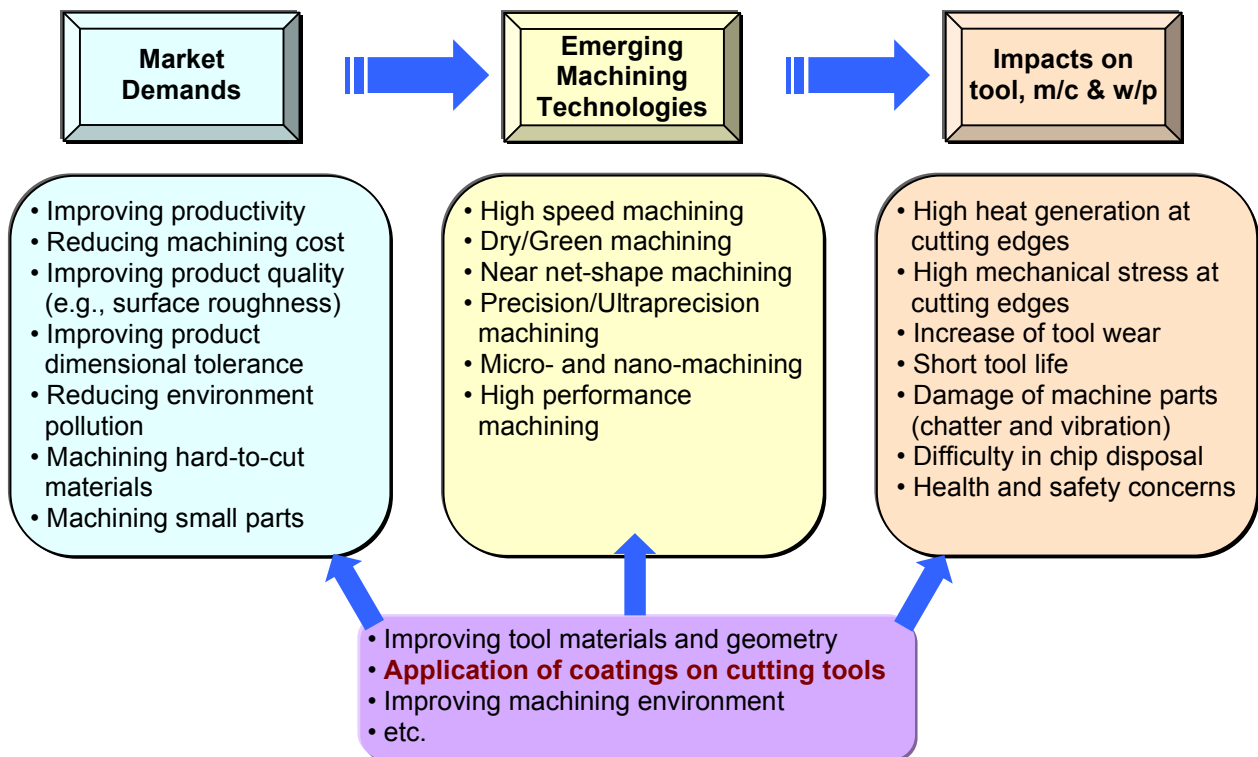


Fig. 1. Challenges and advancements in metal cutting machining.

Aerospace, automotive, die and mold industries are the front-runners in using the emerging machining technologies such as high speed machining, dry machining, near net-shape machining etc.. The magnitude of cutting forces generated and hence, heat at the cutting edges by these technologies pose a constant threat to the integrity of cutting edge. The cutting tool must resist these severe conditions and provide a sufficiently long and economical tool life. Advanced

coatings could play a major role in solving these problems as they improve the wear resistance of cutting tools during machining by reducing friction, adhesion, diffusion, and oxidation in addition to relieving thermal and mechanical stresses induced upon the tool substrate. It has been estimated that approximately 80% of all cutting tools are currently coated [10] using mainly Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD) technologies with different coating materials such as Titanium Carbide (TiC), Titanium Nitride (TiN), Titanium Carbonitride (TiCN), Aluminum Oxide (Al_2O_3) etc..

This paper aims to outline different aspects of developing advanced coating technologies for metal cutting machining with some selected examples of machining tests conducted using multipoint coated cutting tools.

2. EXPERIENCE WITH TiN COATED MULTIPOINT CUTTING TOOLS

Since 1970's Titanium Nitride (TiN) has become a favourite coating on cutting tools as it combines high hardness, high wear resistance, low coefficient of friction, low chemical affinity and moderate thermal stability leading to improved cutting tool performance and product quality in different machining applications. There are claims that 2-5 times improvement in tool life and a 10-50% increase in productivity can be achieved depending on the workpiece material being machined, type of machining, cutting conditions etc. [1]. TiN coating is still dominant in the marketplace owing to its reliability in performing for most of the machining applications and workpiece materials and affordable cost. The machining operation with multipoint cutting tools such as bandsaw, circular saw, milling cutter, broach tool etc. is different from single point lathe tool due to complex cutting edges, relatively poor sharpness of the cutting edges, complex combination of chip formation mechanism, intermittent cutting action and difficulty in accommodating chips in limited gullet sizes [11]. Again, relatively less accuracy and consistency in manufacturing individual cutting edges of multipoint tools results in varying tool performance. Majority of research work has been focused on single point tools while there are limited efforts in evaluating the performance of coated multipoint tools [6, 12-14]. The following sections present some of the machining test results experienced with TiN coated multipoint cutting tools. Flank wear measurement, cutting time/section, and specific cutting energy were used to evaluate the performance of coated tools.

2.1 Milling Cutter

Fig. 2 shows the results of flank wear in TiN coated and uncoated teeth of a High Speed Steel (HSS) milling cutter used for manufacturing bandsaws. It is evident that the coating has reduced the flank wear up to 40% compared to the flank wear in uncoated teeth. However, the performance of TiN coating in reducing the flank wear is not always consistent showing little or no improvement in few teeth. Complex cutting action by the multipoint milling cutters, lack of manufacturing accuracy and variation in coating thickness ($2\ \mu\text{m}$ - $4\ \mu\text{m}$) along the cutting edge of individual tooth could be attributed to this kind of variation.

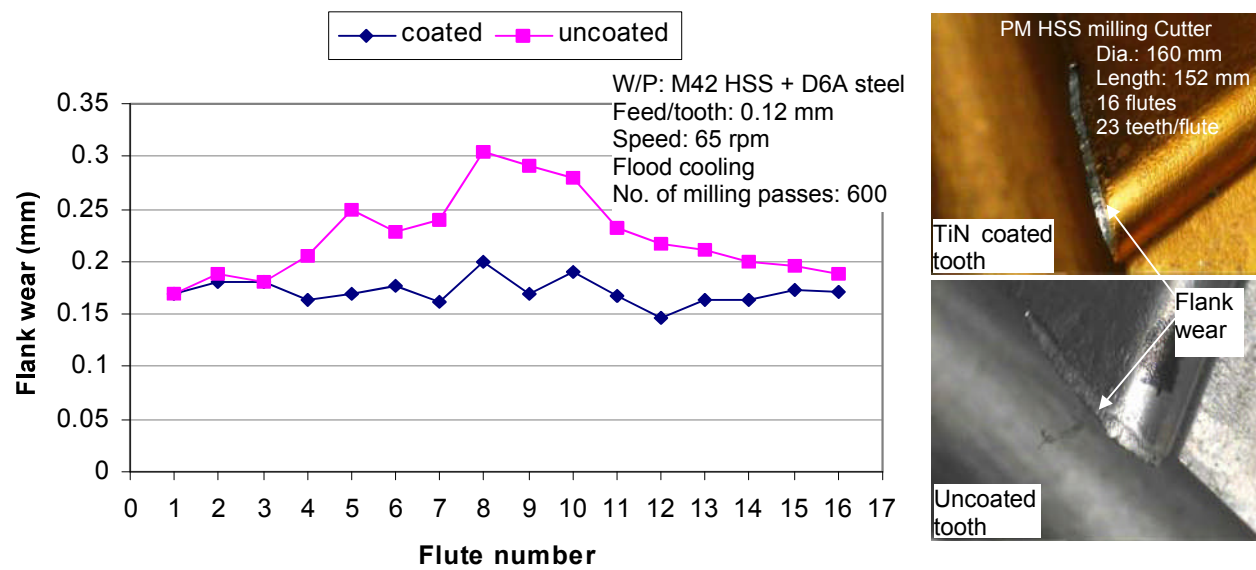


Fig. 2. Flank wear in TiN coated and uncoated teeth of a half-length coated milling cutter.

2.2 Bandsaw

Significant improvement in cutting performance has been realised with TiN coated bandsaw blades (Fig. 3). However, TiN coating failed to contribute in improving the tool life of bandsaw. The variation in geometry (e.g., back to tip height) produced during bandsaw manufacturing could be responsible for inefficient cutting even with TiN coating.

2.3 Circular Saw

The improvement in performance with TiN coated HSS circular saw blades is highlighted in Fig. 4, where a marked reduction in specific cutting energy with coated saw blades is noticed. The lower specific cutting energy with the coated circular saw is due to a combination of flat chip formation and easy chip flow over the rake face [12]. Furthermore, reduction in friction on

the face/sides of the saws reduce forces, torque etc.. This improvement in performance has been achieved with TiN coatings despite the poor surface of the edges prior to coating application.

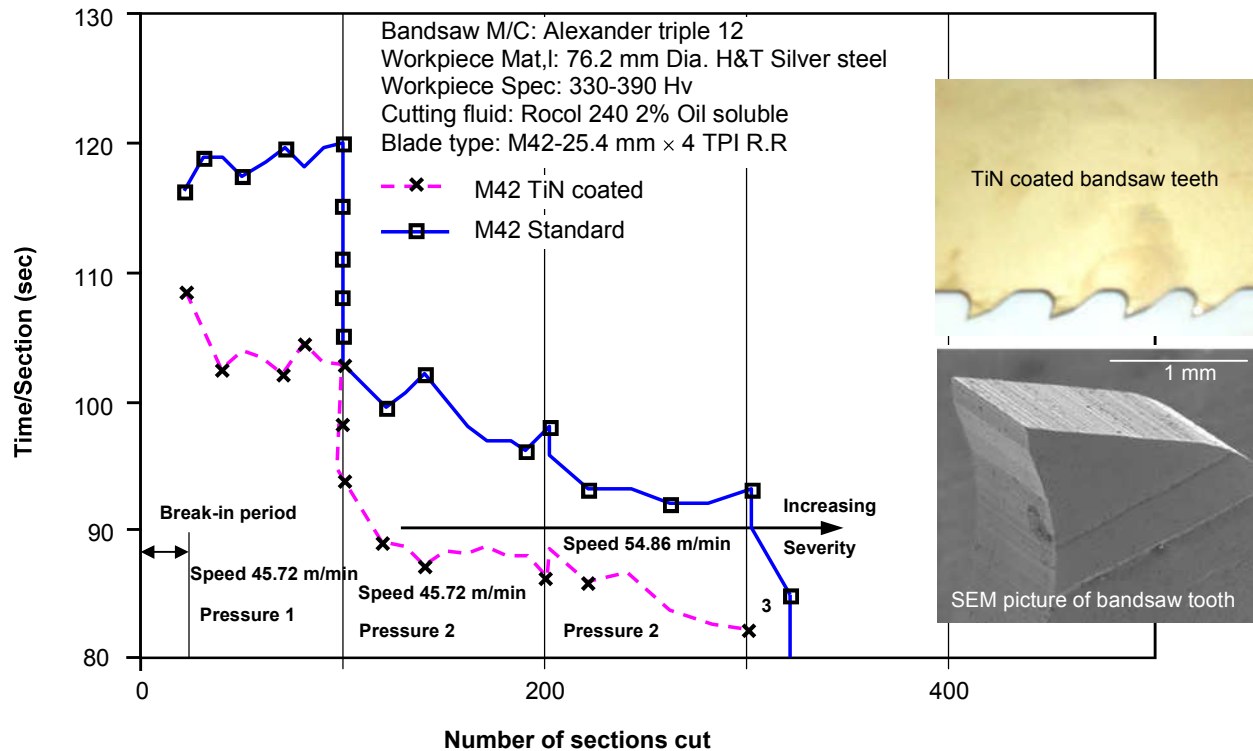


Fig. 3. Comparison of performance between TiN coated and uncoated bandsaws.

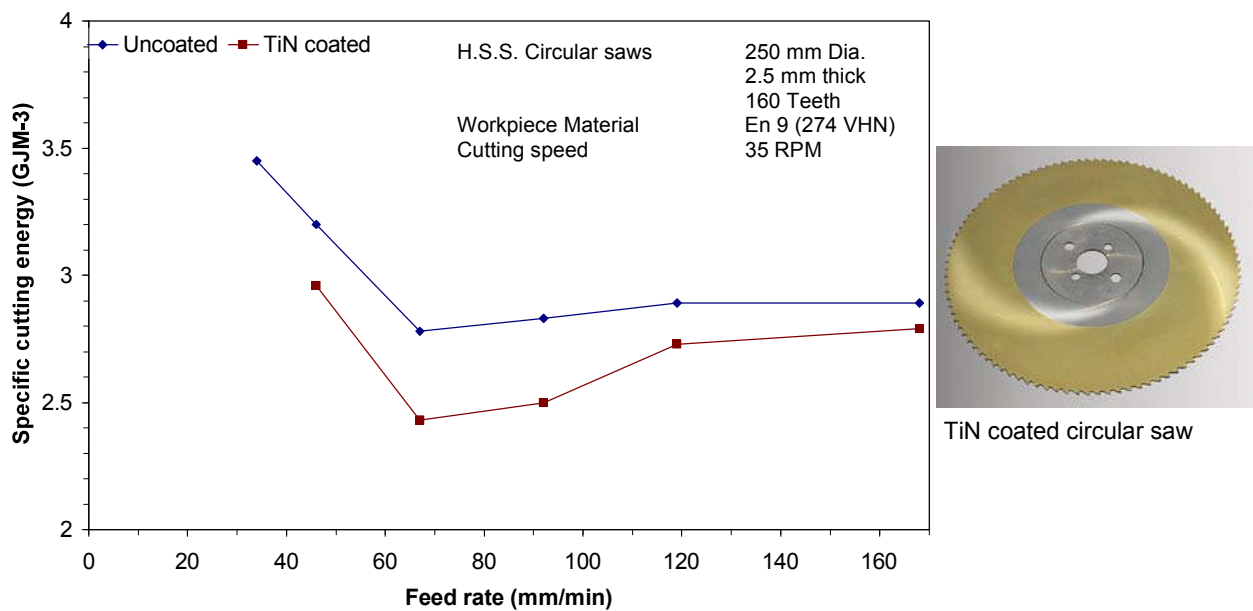


Fig. 4. Performance of TiN coated and uncoated H.S.S. circular saws.

2.4 Holesaws

Holesaws, which are becoming popular in the professional market for making accurate holes, showed a considerable increase in life when coated with TiN coating (Fig. 5). However, premature failure did occur in some cases and this was due to manufacturing faults such as poor welding junction and geometrical error. There is clear evidence that the gullet-filling phenomenon does not prematurely lead to a saw failure, the normal wear pattern occurs in the set teeth and this wear can be reduced and hence the saw life increased by TiN coating.

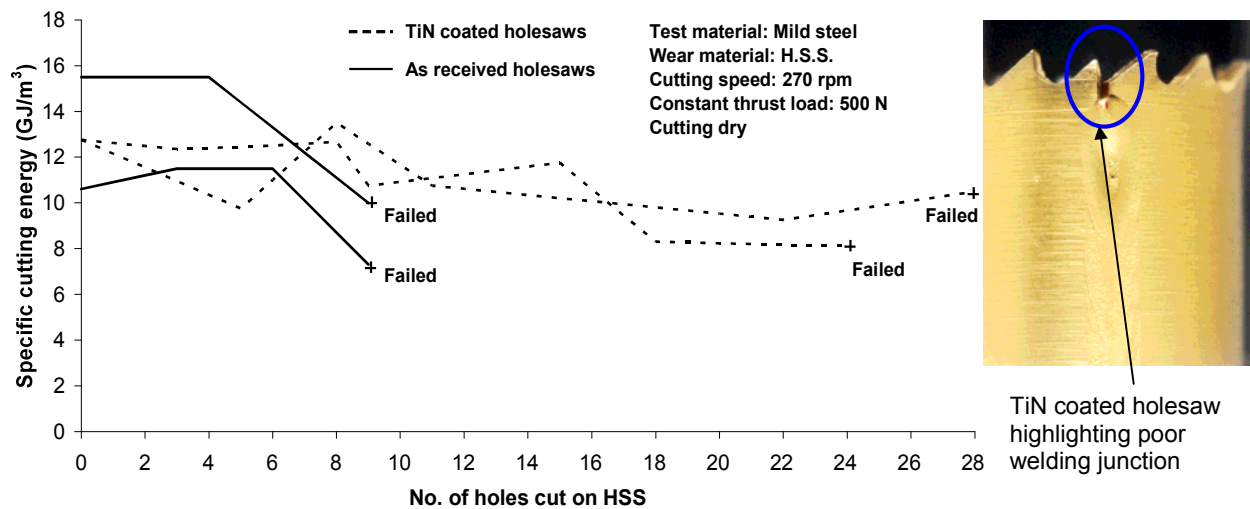


Fig. 5. Performance of 20-mm holesaws.

3. CURRENT TRENDS OF ADVANCED COATINGS FOR CUTTING TOOLS

In addition to the well-established monolayer single-phase coatings such as TiN, TiC etc., efforts have been made in developing several new coating architectures such as multicomponent, multiphase, multilayer, gradient, superlattice, nanocomposites etc., which promise better performance for tough machining applications [8, 15]. With the success of monolayer coating, numerous multicomponent coatings have evolved in response to the demand from cutting tool industries (e.g., higher wear and oxidation resistance). AlTiN and AlCrN are the prime examples that are being applied in high speed and dry machining applications owing to their high wear resistance at elevated temperatures (1000 °C) [16]. The multilayer coating is more resistant to cracking which makes the coating stronger on cutting edges that experience mechanical shock from difficult-to-machine materials and in interrupted cutting (Milling, Hobbing etc.). Multilayer PVD coatings have already seen greater use in industrial applications. The envelope has been

pushed even further with superhard nanostructured composite coatings, a new branch of materials that offer the opportunity to design unique physical and mechanical properties for specific application areas. Nanocomposite coatings have proven to deliver high hardness of 40 to 50 GPa and high heat resistance of up to 1,100° C, making them suitable for dry and high speed machining [17]. The nanocomposite coatings are becoming available in the commercial production for machining applications. Hard-solid lubricant based coatings, which combine low friction soft material (e.g., MoS₂, WS₂, diamond-like carbon) and wear resistant hard material (e.g., TiN, TiAlN etc.) in the form of bilayer, multilayer or composite, are also promising for dry machining. There is also considerable interest in developing crack-free, defect-free, smooth and thin PVD Al₂O₃ coating to outperform thick CVD Al₂O₃ coatings [18].

A variety of superhard coating materials have also been developed such as cubic boron nitride (c-BN), diamond-like carbon (DLC), carbon nitride (a-CN_x) and polycrystalline diamond. Despite having superhardness nature of these coatings, they have found limited machining applications due to lack of thermodynamic stability, high internal stress leading to poor adhesion and high chemical affinity in machining ferrous materials [19].

4. A SYSTEMS APPROACH FOR SURFACE ENGINEERING OF CUTTING EDGES

The common misconception among the wider industrial sector is that surface engineering through the application of coatings is just an add-on process to enhance the performance and life of the tool. Very often, no consideration is given to processes prior to or following surface engineering. Surface engineering must be considered as more than an add on process to achieve the best results. Again little consideration has been given to selecting the appropriate coating for any particular tool material, machining application and workpiece material combination, as there is no single universal coating for all applications. Tool manufacturers have often blamed the coating companies for their product failures whereas in reality coating the tools may have done nothing but highlight inadequacies in other manufacturing tasks. Lack of communication, interdisciplinary training and skills has generally failed to isolate the real cause of tool weakness. A scientific approach is required to understand and solve these problems to achieve the goal of improved tool performance. In order to optimise performance from a surface engineering treatment, a total systems approach is necessary by combining the knowledge of cutting tool manufacturers, surface coaters and end users as shown in Fig. 6 [20].

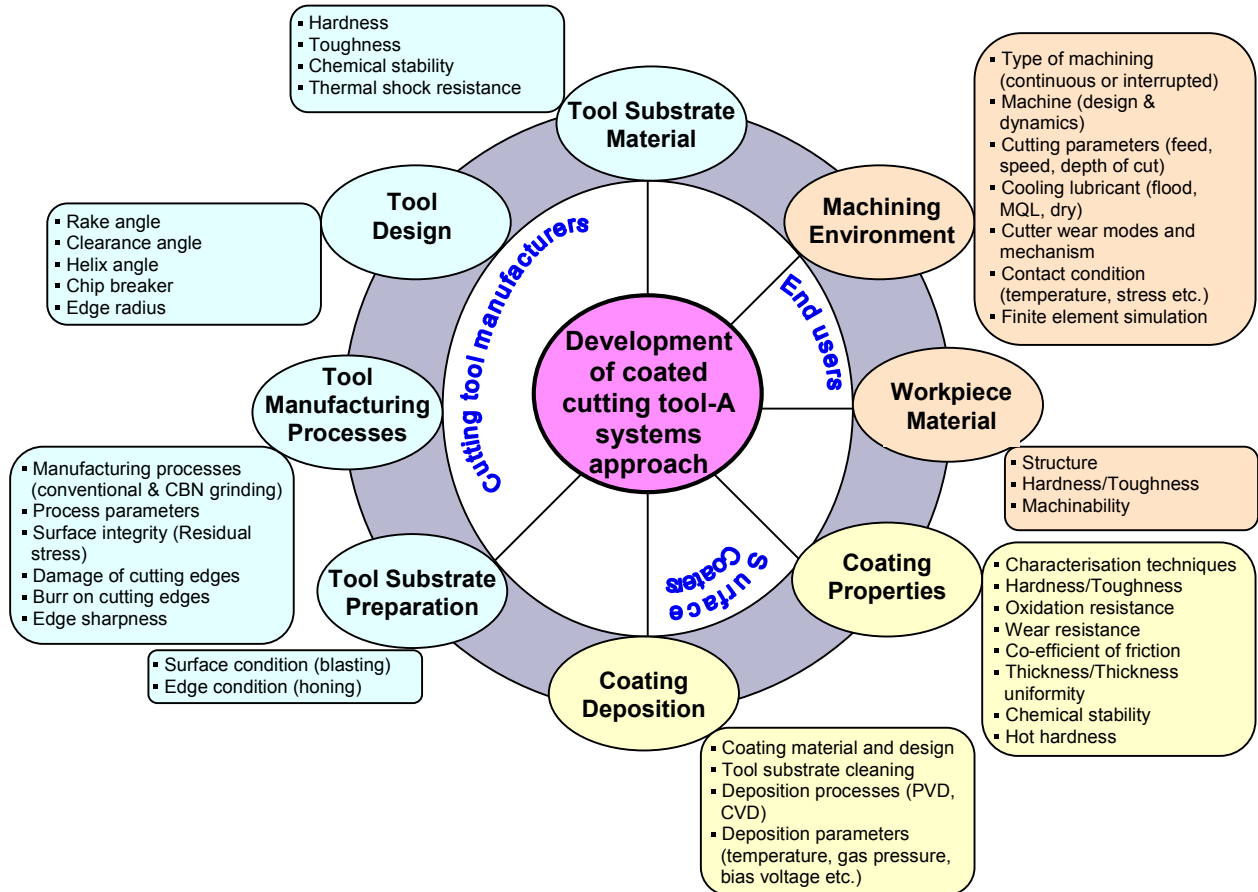


Fig. 6. A systems approach for the development of coated cutting tool.

4.1 Cutting Tool Manufacturers

The first step toward developing successful coated tools is to select the appropriate tool substrate, though the factors associated with coating and machining are important. The desirable material characteristics of tool substrate are fracture strength, resistance to plastic deformation and hardness, which are typically controlled by composition and microstructure of the substrate. For example, Powder Metallurgy (PM) HSS broach tools show improvement in quality of cutting edges and tool life due to uniformly distributed fine grain carbides leading to improved toughness and strength without compromising the hardness [13]. The hardness and toughness in the tool substrate material must be balanced to maintain the stability and integrity of the cutting edges. Today, Tungsten carbide (WC) and HSS comprise 95% of the cutting tools used worldwide, while more than 50% tools are made of WC [6].

The geometry of the cutting tools has a significant effect on the chip formation mechanism, cutting forces, tool life, machined surface quality etc.. Experience has shown that 70% of a

cutting tool's performance is based on geometry and 30% on coating or substrate [11, 21]. Therefore, application of coatings on cutting tool can deliver the desired machining results when cutting tool macro- (e.g., rake angle, clearance angle, chip breaker, helix angle etc.) and micro-geometry (e.g., edge radius) are appropriately designed depending on the cutter material, machining applications and workpiece materials.

The edge conditions (e.g., edge sharpness, burr, edge damage, edge burning etc.) of cutting tools after its manufacturing are also critical to their stability, reliability and life expectancy in use. Cutting edges produced by grinding have an estimated edge radius $5\text{ }\mu\text{m}$ - $20\text{ }\mu\text{m}$, whereas milling produces typical edge radius of $30\text{ }\mu\text{m}$ - $70\text{ }\mu\text{m}$. The initial breakdown of a coated edge owing to a burr would expose the substrate and hence, not show the full benefits of coating. Furthermore, the handling of the sharp cutting tools, particularly multipoint cutting tools is very critical, because damaged cutting edges will not be able to take the full advantage of coatings. Aggressive grinding practices, such as rough or dry grinding that leave damaged surface layers on the tool, must be avoided. The use of appropriate manufacturing tools (grinding wheel or milling cutter), optimum manufacturing process parameters and appropriate handling tools could eliminate these manufacturing faults prior to the application of coatings. Fig. 7 shows the cutting edges as produced by a manufacturer highlighting the conditions of the cutting edges prior to the surface treatment.

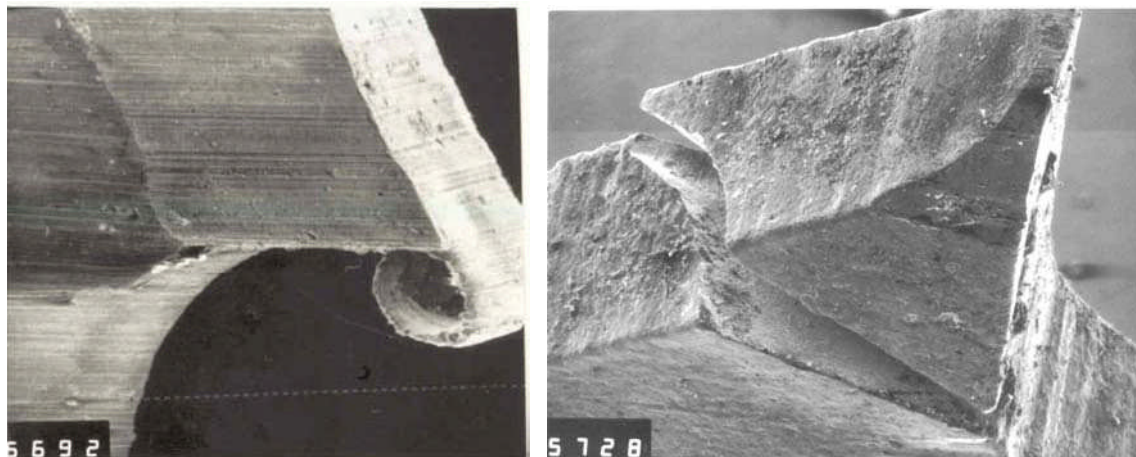


Fig. 7. Cutting edge characteristics of (a) a circular saw tooth and (b) a bandsaw tooth.

It is clear from the SEM pictures that cutting edges produced in multipoint cutting tools such as bandsaws or circular saw blades are inferior in quality compared with those on single point tools. This reflects the higher level of control on cutting edge geometry associated with powder

metallurgy techniques. It is not surprising that manufacturers of multipoint cutting edge tools have not had the same level of improvement in the product as single point lathe tools.

Another key factor in improving machining performance with coated tool is the preparation of tool substrate and cutting edges prior to application of coating. Microblasting or water peening of tool substrate before coating application removes manufacturing defects (e.g., grinding marks) or loose superficial layers, changes the subsurface characteristics (e.g., compressive stress) with positive effects and improves surface finish [11, 22-23]. All of these factors contribute to the growth of fine-grained and dense coating microstructure on the tool, increased coating adhesion and thickness uniformity, which lead to enhancement in machining performance. Cutting tool manufacturers and surface coaters are also quickly realising that it is difficult to coat sharp edges and furthermore, once coated, the edges are not retained. Therefore, there is need to modify and redesign the edges, which would retain the strength suitable for the advanced coatings. Cutting edge treatment prior to coating application such as honing produces easy-to-coat radiused edge with improved edge stability. This also improves coating uniformity and mechanical properties at the cutting edges, which means higher metal removal parameters can be used to boost the productivity [24]. Typical edge radius of 10 μm - 25 μm is beneficial for improving machining performance. Cutting tools need to be prepared to stringent quality standards before coating and important parameters need to be measured in each stage of manufacturing process starting from raw material to finished tool ready for coating. Large cutting tool manufacturers are currently focusing on integration of coating technology in tool manufacturing processes to eliminate issues related to quality of coated tools. To the best knowledge of authors, there is no complete standard specification of tool cutting edges and surface characteristics prior to coating application. There is a need for better specification based on scientific evidences.

4.2 Surface Coaters

Surface coaters should be careful about selecting the coating material (e.g., TiN, AlTiN) and design of coating architecture (single layer or multilayer) to match with the machining application (continuous or interrupted). As substrate cleanliness plays a major role in the coating's adhesion, strict control of tool cleaning procedure and clean environment are essential. Coating performance in metal cutting tools still varies widely depending upon coating processes (e.g., arc evaporation, sputtering etc.) and deposition parameters. Therefore, it is critical to determine coating composition and specific process technology, which are best suited to any

particular tool under specific operating conditions. PVD technology is gaining increasing market share owing to its ability to deposit thin coating (micrometre to nanometre), low deposition temperature (450 °C and below) and better coating properties [25-26]. It has been estimated that in 2007 globally 56% of cutting tools are coated by PVD technology as compared to 20% in 2000 [27]. The control of deposition parameters such as gas pressure, deposition temperature, bias voltage etc. is also very critical to achieve the optimum coating properties [15, 28]. With the advent of computer technology, it has become easier to operate and control vacuum coating equipment, however, discipline is required in the area of preventative maintenance and operating procedures to avoid any hidden process instability [29]. Coating properties and thickness could also vary depending on the size and shape of the cutting tool [29]. This is particularly critical for complex shaped multipoint cutters (e.g., milling cutter). Therefore, coating properties must be optimised for a particular shape and size of cutter and different shaped and sized cutters shouldn't be coated in the same batch to avoid any variation in coating properties. Coating companies are also considering the post-treatment (e.g., polishing, microblasting) of coated cutting edge to improve smoothness and to reduce residual stress by removing defects in the coating, but post treatment could cause local removal of coating in case of rougher substrate leading to poor cutting performance [23].

From the metal cutting machining point of view, maximum benefit in terms of machining performance and tool life can be achieved when the coating possess a favourable combination of intrinsic properties (e.g., hardness, toughness, chemical inertness, adhesion etc.) [16, 28], as they determine the tribological properties (e.g., wear, coefficient of friction etc.) at the tool-workpiece contact point [15]. Hence, urgent attention is required in accurately evaluating both intrinsic and tribological properties using specified test equipments, as the coating is quite thin (3 µm - 5 µm). There exists a lack in certified methods of testing which needs to be standardised to compare different published results [29-30]. Above all, integration of a well-defined quality control system in every steps of coating deposition and evaluation processes will ensure the desired quality of coating.

4.3 Cutting Tool End Users

It is well established that the properties of workpiece material particularly yield stress dictates the chip formation mechanism, which also influences the cutting forces, tool tip temperature, cutter performance and finally the cutter life [31]. The end users of cutting tools

should assess workpiece properties beforehand to select the compatible coating for optimum machining.

Surface coatings are clearly valuable in extending the life of cutting tool by arresting or slowing down wear and in improving the quality of the machined surface. The extension of tool life with coatings even when operated at the conventional machining parameters reduces cost associated with tool and tool changing time, but it has very little contribution in increasing the productivity or reducing the machining cost, as cutting tool cost is only 3-5% of total machining cost [16]. A user of coated tools will financially benefit (lower the cost of the operation by reducing cycle times) only when the coated tool is used at high feeds and speeds. As a rule of thumb, cutting parameters can be increased from 20% to 50% with a coated tool [32] depending on the type of machining and workpiece material to be machined. Improved machine tool stability is vital to fully exploit the potential of coated tools by operating at high metal removal rates. Wear modes (crater, flank and notch wear) and mechanisms (abrasive, adhesive and diffusive wear) in cutting tools for a particular application need to be evaluated to select the appropriate coating. Ideally, the coating on the cutting tool should fail by gradual wear associated with predictable and reliable tool performance, but not by adhesive or cohesive failures, macro-/micro-chipping etc., which rapidly raises cutting forces and tool tip temperatures leading to a premature tool failure. Finite element modeling could be used as a potential supplementary tool in addition to the experimental investigation to simulate stress and heat generation in coated cutting tools [33].

5. CONCLUDING REMARKS

Examples of machining test results demonstrated that TiN coating applied on multipoint cutting tools (milling cutter, bandsaw, circular saw, holesaw etc.) could deliver considerable improvement in machining performance and product quality. However, it is apparent that manufacturing method and quality control of multipoint cutting edges must be fine-tuned before realising substantial improvement in performance and reliability with advanced coating applied onto them. Undoubtedly, TiN coating on cutting tool will continue to be a choice in the cutting tool industry, while the other more advanced coatings such as AlTiN, AlCrN, TiSiN etc. will slowly enter into the cutting tool industry where high wear and oxidation resistance are primary concerns. Current trends suggest that in the next few years the cutting tool industry will see

widespread application of advanced nanocomposite coatings, which offer the possibility of tailored made multifunctional properties (e.g., super-hardness, toughness and oxidation resistance) for particular applications. In order to gain maximum benefit from surface engineered tools, a total systems approach based on substrate materials, tool design, manufacturing processes and quality control are absolute vital.

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References

- [1] K. Holmberg and A. Matthews, Coatings Tribology, Amsterdam: Elsevier; 1994.
- [2] Oerlikon, Balzers. <http://www.oerlikon.com/balzers/>
- [3] IonBond. <http://www.ionbond.com/>
- [4] CemeCon. <http://www.cemecon.de/>
- [5] Sandvik. <http://www.coromant.sandvik.com/>
- [6] S.R. Bradbury, D.B. Lewis, P.M. Archer, W. Ahmed, Impact of surface engineering technologies on the performance and life of multipoint cutting tools, *Surf. Coat. Technol.*, Vol. 91 (1997) 192-199.
- [7] S.R. Bradbury and T. Huyanan, Challenges facing surface engineering technologies in the cutting tool industry, *Vacuum*, Vol. 56 (2000) 173-177.
- [8] G. Byrne, D. Dornfeld, B. Denkena, Advancing Cutting Technology, *CIRP Annals – Manuf. Technol.*, Vol. 52 (2003) 483-507.
- [9] F. Klocke and T. Krieg, Coated Tools for Metal Cutting - Features and Applications, *CIRP Annals – Manuf. Technol.*, Vol. 48 (1999) 515-525.
- [10] J. Rech, Influence of cutting tool coatings on the tribological phenomena at the tool–chip interface in orthogonal dry turning, *Surf. Coat. Technol.*, Vol. 200 (2006) 5132-5139.
- [11] D.B. Lewis, S.R. Bradbury, M. Sarwar, Effect of substrate surface preparation on the performance and life of TiN-coated high speed steel circular saw blades, *Surf. Coat. Technol.*, Vol. 82 (1996) 187-192.
- [12] M. Sarwar, X. Zhang, D. Gillibrand, Performance of titanium nitride-coated carbide-tipped circular saws when cutting stainless steel and mild steel, *Surf. Coat. Technol.*, Vol. 94-95 (1997) 617-631.
- [13] M. Sarwar, Application of advanced surface engineering treatments to multi-point cutting edges, *Surf. Coat. Technol.*, Vol. 108-109 (1998) 612-619.
- [14] M. Sarwar, D. Gillibrand, S.R. Bradbury, Forces, surface finish and friction characteristics in surface engineered single- and multi-point cutting edges, *Surf. Coat. Technol.*, Vol. 41 (1991) 443-450.
- [15] S. Hogmark, S. Jacobson, M. Larsson, Design and evaluation of tribological coatings, *Wear*, Vol. 246 (2000) 20-33.

- [16] W. Kalss, A. Reiter, V. Derflinger, C. Gey and J.L. Endrino, Modern coatings in high performance cutting applications, *Int. J. Refract. Met. Hard Mater.*, Vol. 24 (2006) 399-404.
- [17] S. Veprek and M.J.G. Veprek-Heijman, Industrial applications of superhard nanocomposite coatings, *Surf. Coat. Technol.*, Vol. 202 (2008) 5063-5073.
- [18] M. Åstrand, T.I. Selinder, F. Fietzke, H. Klostermann, PVD-Al₂O₃-coated cemented carbide cutting tools, *Surf. Coat. Technol.*, Vol. 188-189 (2004) 186-192.
- [19] J. Musil, Hard and superhard nanocomposite coatings, *Surf. Coat. Technol.*, Vol. 125 (2000) 322-330.
- [20] M. Sarwar and W. Ahmed, A systems approach to surface engineering of cutting edges, *Mater. World* (1994) 141-143.
- [21] D. Esford, A Cut Above, *Cutting Tool Engineering plus*, Vol. 51(1999).
- [22] H.K. Tönshoff, B. Karpuschewski, A. Mohlfeld, H. Seegers, Influence of subsurface properties on the adhesion strength of sputtered hard coatings, *Surf. Coat. Technol.*, Vol. 116-119 (1999) 524-529.
- [23] K.-D. Bouzakis, N. Michailidis, S. Hadjiyiannis, K. Efstathiou, E. Pavlidou, G. Erkens, S. Rambadt, I. Wirth, Improvement of PVD coated inserts cutting performance, through appropriate mechanical treatments of substrate and coating surface, *Surf. Coat. Technol.*, Vol. 146-147 (2001) 443-450.
- [24] J. Rech, Y.-C. Yen, M.J. Schaff, H. Hamdi, T. Altan, K.D. Bouzakis, Influence of cutting edge radius on the wear resistance of PM-HSS milling inserts, *Wear*, Vol. 259 (2005) 1168-1176.
- [25] D.T. Quinto, Technology Perspective on CVD and PVD Coated Metal-Cutting Tools, *Int. J. Refract. Met. Hard Mater.*, Vol. 14 (1996) 7-20.
- [26] S. Söderberg, M. Sjöstrand, M. Lgunberg, Advances in coating technology for metal cutting tools, *Met. Powder Rep.*, (2001) 24-30.
- [27] Coating catch-up, www.machinery.co.uk
- [28] H.G. Prengel, W.R. Pfouts, A.T. Santhanam, State of the art in hard coatings for carbide cutting tools, *Surf. Coat. Technol.*, Vol. 102 (1998) 183-190.
- [29] C. Friedrich, G. Berg, J. Senf, E. Broszeit, Reliable PVD coatings on components: aspects of deposition and characterization for quality management, *Surf. Coat. Technol.*, Vol. 112 (1999) 152-161.
- [30] H.R. Vettters, A. Schulz, P. Mayr, S.R.J. Saunders, Characterization and properties of hard coatings: international standardization efforts, *Surf. Coat. Technol.*, Vol. 86-87 (1996) 345-350.
- [31] C.Y.H. Lim, P.P.T. Lau, S.C. Lim, The effects of work material on tool wear, *Wear*, Vol. 250 (2001) 344-348.
- [32] W. Mielert, Coating for Speed, *Cutting Tool Engineering plus*, Vol. 48 (1996).
- [33] D. Gillibrand, S.R. Bradbury, A. Yazdanpanah, S. Mobayyen, A simplified approach to evaluating the thermal behaviour of surface engineered cutting tools, *Surf. Coat. Technol.*, Vol. 82 (1996) 344-351.